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Interrelations of Arctic Ice with the Ocean and the Atmosphere in the North Atlantic-Arctic and Adjacent Areas

by

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Summary

A comparison was made of the mean April-August sea ice limit of the Greenland and Barents Seas with the contemporary and following seasons air temperature and precipitation of Iceland and sea surface temperatures in the northern North Atlantic, and of the decadal variations in the Arctic ice with the corresponding variations in the sea surface temperature, precipitation and storminess in that general area. The results indicate the Arctic ice during April-August to be a substantial measure of the following September to February sea surface temperature off the east coast of Iceland and the Faroes and of Iceland's September-February air temperature, and that the decadal variations in the ice are a measure of the decadal ocean and weather trends in the northern North Atlantic and adjacent areas.

A. Introduction

The aim of this study is to outline, with the aid of the growing body of Arctic ice and oceanographic and meteorological data, the nature and degree of interrelation between the severity of the Arctic ice in the northern North Atlantic and the seasonal, annual, and longer-period variations in ocean and air temperatures, precipitation, and storm frequencies and mean storm tracks in that general area.

Recognizing that the variations in the Arctic ice are determined by winds, currents, sea and air temperatures, etc., it is evident that, insofar as relationships of the Arctic ice with the preceding conditions in the ocean and the atmosphere can be established, a basis will have been obtained for foreshadowing the ice conditions; and, insofar as relationships with the following temperatures, etc., can be defined, a basis will have been derived for foreshadowing the general character of the weather, etc., in the Arctic and adjacent areas. Thus, the problem of Arctic ice relationships may be divided into two phases: relationships of the ice with the preceding ocean and air circulation and relationships of the ice with the contemporary and following ocean and weather conditions and although the two phases are interrelated they can be treated separately. The following will deal with the second phase of this problem. Also, since the Arctic ice record considerably antedates the earliest meteorological and oceanographic observations in the Arctic and adjacent areas, an outline of the relationships of the Arctic ice with the air and ocean temperatures, etc., in the Arctic and adjacent areas would provide valuable information on earlier oceanographic and meteorological conditions in those areas.

B. Data and Method of Study

The ocean areas from which Arctic ice data are available for longer periods of time are (1) the waters off Iceland (1750's on) and the Greenland Sea in general (1877-), (2) the Barents Sea

(1895-), (3) the waters off southwest Greenland (1820-), (4) the waters off Newfoundland (1861- , approximately; principally iceberg counts), (5) the Bering and Chuckchee Seas (1899-) and others.

Only the ice data from areas (1), (2), and (3) embracing the Greenland and Barents Seas could be treated in this investigation. The southerly limits of the ice in the two areas that were used in this study were taken from compilations made by the Danish Meteorological Institute, and the values designating the severity of the ice off Iceland, from a recent compilation by Koch (1945). The air temperature and precipitation data were, for the most part, taken from World Weather Records. The sea temperature data came mainly from a series of recent papers by Smed (1947-1953) and from a paper by Brown (1953). Further details about the data, including the storm frequencies also studied here, will be found in the appropriate sections dealing with them. In a considerable measure, the data for recent years were obtained by correspondence; and the author wishes to express his gratitude to all those who have contributed in this respect.

The various ice data were then correlated with different oceanographic and meteorological data from the Arctic and adjacent areas by season, year, and decade; and the results of the correlation are shown in the tables below. In those instances where use was made of the correlation coefficient r, it was only to measure an association, anticipated in general terms from physical considerations; and as the question of the significance level of the derived coefficients did not apply, it was not considered. Were these coefficients compared with the "largest possible by chance", it would have led to misleading results since the coefficients that fall below its value indicate a relationship as real as those that match it or exceed it.

C. Brief Statement of Problem

Because the two large polar ice areas in the Arctic and Antarctic, respectively, are a prominent factor in the general circulation of the atmosphere and the hydrosphere, significant changes in their areal extent might be associated with changes in the atmosphere and the ocean in the high latitudes and, also to a lesser extent, with changes in the circulation in lower latitudes.

In general, severe ice conditions off Iceland and a more southerly extension of the Arctic ice pack in the Greenland Sea, for example, might be expected to be associated with a well-developed polar High, a less developed North Atlantic Low, and with a shift of this Low southward. This tendency for a reorientation in the pressure distribution associated with a more southerly position of the Arctic ice limit is associated also, we may assume, with a more southward extension of the colder polar water and, therefore, with a southerly displacement of the zone of sharp temperature contrasts between the southward flowing cold

polar water and the northward flowing warm Atlantic water. In addition, since the mean storm track in the northern North Atlantic is presumably associated with the zone of sharp temperature contrasts, we might expect also a shift of this storm track southward and, consequently, an increase in the storminess in lower, and a decrease in higher, latitudes. Thus the pressure could be expected to be lower and the precipitation higher in the zone of increased storminess (to the south) and, conversely, higher and lower, respectively, in the zone of decreased storminess (to the north).

Additionally, because of a tendency for marked persistence in the ocean and to a lesser extent in the atmosphere, the state of the ocean and the atmosphere following one or another type of ice conditions may also be expected to persist, and, therefore, also, for the following ocean circulation and weather patterns to be related to the Arctic ice.

D. Previous Investigations

For earlier work in this field, the reader is referred primarily to a paper by Wiese (1924) and, for a recent extension, to a work by this author (Schell, 1947, see also 1940) in which the relationship between the variations of the ice in the Greenland Sea (April-August) and the following precipitation in northwestern Europe was considered on the basis of 56 years of data then available. In conformance with the pattern of Arctic ice-weather relationships drawn above, the average precipitation following severe ice conditions was found heavier than usual south of 60°N (the area of the British Isles, Denmark, northern France, southern Norway, and Holland), where an excess of storminess would be expected, but lighter than usual over northern Norway, where a deficiency would be expected following the same type of ice conditions.

In addition to the earlier indicated relationships of the Arctic ice with the contemporary and following season's pressure distribution, mean storm track and storm frequency, temperatures, and the precipitation, a similar relation between the decadal character of the ice off Iceland* and the temperature of several Arctic fringe areas and of other areas in lower latitudes was determined (Schell, 1952). The results covering the period 1831-1950 showed the severe ice decades during this 120-year period to be associated with negative temperature deviations and the light ice decades with positive temperature deviations, the relation of the ice with the temperature of the stations in the Arctic fringe areas being the closer. However, in addition to the relation of the ice with the contemporary temperature, a relation was also found with the following decadal temperature in Stykkisholm,

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* The decadal character of the ice off Iceland usually reflects the ice conditions over a much wider area.

Archangel, and to a lesser extent, Vardo. At Archangel, where the effect of local persistence of severe ice conditions and the associated cold water, for example, may be expected to be strengthened by a greater dilution of the northeastward flowing warm Atlantic water by a stronger East Icelandic Polar Current during severe ice periods, the temperature deviation (negative sign) of the decade following a severe ice decade was found actually greater than the deviation corresponding to the severe ice decade itself (Schell, 1952).

E. Present Investigation

The plan of the current investigation was to broaden the relationships of Arctic ice with the contemporary and following ocean and air temperatures, etc., by employing 1) longer records of the Arctic ice, temperature, precipitation, etc., that have since become available, and 2) observations from additional areas, and 3) observations for additional seasons. In addition to the Greenland Sea ice and the ice off Iceland series that were previously generally employed, a series combining the Greenland and Barents Seas ice limits was also used. The respective ice series were next correlated with the contemporary and the following season's temperature and precipitation of Iceland. A separate investigation was also made of the relationships between the Greenland Sea ice and the large body of sea surface temperature data of the northern North Atlantic (north of 50°N) that has recently become available, and the data from the fixed stations along the coasts of Norway, Iceland, etc. Additionally, a correlation was made of the month to month change in the net air transfer in the Arctic with the changes in the ice area. Also, the character of the decadal relationships with the ice was further investigated by treating, in addition to the air temperature, the sea surface temperatures, the precipitation of Iceland and northern Europe, as well as the storminess over the northern North Atlantic.

1. Relationships with the contemporary and following temperature of Iceland.

In line with the general relationship of a more polar trend in the weather and the ocean, with severe as compared with light ice conditions, we should expect the temperature of Iceland and adjacent areas during and also for a period of months following a severe ice season, to show a tendency for below normal and, during and following a light ice season, for above normal, values.

In an attempt to measure this relationship, the Greenland Sea ice series, dating from 1881, as well as the shorter Greenland and Barents Seas ice series combined, dating from 1895, were correlated with the mean temperatures of the March-May, June-August quarters contemporary with the ice season; next with the temperatures of the following September-November, December-February, March-May quarters at Berufjord on the east coast and at Stykkisholm on the west coast of Iceland; and then correlated with the temperature of the two contemporary and the two

immediately following seasons and for both stations together. Another correlation was carried out with the annual air temperatures. The two sets of correlation coefficients based on data ranging from 64 to 50 years are shown for each of the quarters, etc., contemporary with and following the ice season in Table 1.

It is evident from the negative sign of the correlation coefficients derived throughout that there is a tendency for below normal temperatures contemporary with and following a severe ice season and, correspondingly, for above normal temperatures contemporary with and following a light ice season. It also appears that when the temperatures of these two stations are considered together, as well as when the values of the temperatures are averaged for the two seasons that are contemporary with and the two that follow the ice season, the correlation coefficients obtained are not infrequently higher than those obtained with each of the seasons or stations singly. The frequent closer associations between the Arctic ice and the temperatures employing data from two related (with respect to the ice) stations and two similarly related seasons together are no doubt due to the smoothing out of local influences and to automatic smoothing introduced when combining initially homogeneous time intervals. On the same principle, the annual correlation coefficients also came out frequently higher than any of those for a single quarter. Also, the correlations of the temperature with the ice of the Greenland and Barents Seas combined came out on the whole closer than those with the Greenland Sea ice alone (Table 1), indicating that the ice of the larger area is a better index of the contemporary and following circulation processes in that general area than the Greenland Sea ice alone. (The definition here obtained of the association between the temperature with the ice of the Greenland Sea alone must be regarded as firmer, however, since the Greenland Sea ice series is longer by thirteen years. Nevertheless, it would be correct to expect that a larger ice area would relfect conditions more faithfully than a smaller area; and for want of contradictory evidence we must accept the finding that the ice of the Greenland and Barents Seas combined is apparently the better index of the two.)

2. Relationship with the contemporary and following precipitation of Iceland.

As previously suggested, severe ice conditions in the Arctic are presumed to be associated with a greater development of the polar high pressure field and a southerly displacement of the mean storm track in the northern North Atlantic from its usual position and, conversely, light ice conditions with a lesser development of the Polar High and a more northerly position of the mean storm track. Thus, with a tendency towards higher pressure and fewer storms over Iceland with severe as compared with light ice conditions, we should expect lower than usual precipitation during and following severe ice conditions and higher than usual precipitation during and following light ice conditions.

A correlation of the two ice series previously employed with respect to the air temperature was carried out in the same manner

Table 1. Correlation of April-August Greenland Sea ice (A) and Greenland Sea and Barents Sea ice combined (B) with the contemporary and following March-May, June-August, etc., temperature and precipitation of Iceland.

A. Greenland Sea Ice (1881-1892, 1895-1939, 1946-1949)

	Contemporary				Following			
	Mar-May	Jun-Aug	Mar-Aug	Sep-Nov	Dec-Feb	Sep-Feb	Mar-May	Annual
Temperature	r	r	r	r	r	r	r	r
Berufjord	-.18	-.33	-.25	-.24	-.37	-.38	-.20	-.32
Stykkisholm	-.44	-.61	-.52	-.23	-.35	-.34	-.33	-.60
Berufjord and Stykkisholm	-.23	-.36	-.36	-.33	-.37	-.41	-.23	-.41
Precipitation								
Berufjord	-.19	-.37	-.39	-.05	.09	-.04	-.15	-.22
Stykkisholm	-.13	-.42	-.36	-.31	-.35	-.34	-.31	-.50
Berufjord and Stykkisholm	-.22	-.42	-.41	-.23	-.13	-.22		-.42

B. Greenland Sea and Barents Sea Ice (1895-1939, 1946-1949)

	Mar-May	Jun-Aug	Mar-Aug	Sep-Nov	Dec-Feb	Sep-Feb	Mar-May	Annual
Temperature	r	r	r	r	r	r	r	r
Berufjord	-.25	-.32	-.31	-.31	-.51	-.49	-.22	-.42
Stykkisholm	-.35	-.43	-.41	-.38	-.50	-.56	-.23	-.50
Berufjord and Stykkisholm	-.29	-.36	-.36	-.40	-.53	-.54	-.27	-.50
Precipitation								
Berufjord	-.20	-.34	-.45	-.19	-.17	-.23	-.06	-.40
Stykkisholm	-.18	-.37	-.32	-.34	-.41	-.42	-.39	-.55
Berufjord and Stykkisholm	-.26	-.43	-.45	-.34	-.31	-.43	-.30	-.58

as before with the contemporary and following precipitation at Stykkisholm and Berufjord, beginning with the March-May quarter; and the results of the correlation obtained are shown in Table 1. It is again evident from the negative sign of the correlation coefficients throughout, that a tendency exists for below normal precipitation during and following a severe ice season and for above normal precipitation during and following light ice conditions, as anticipated.

As in the case of the temperature, the association of the precipitation with the Arctic ice is frequently closer when the two stations (Berufjord and Stykkisholm), and when the two contemporary seasons (March-May, June-August), and when the two following the ice seasons (September-November, December-February) are treated together. Also, the association on the whole is closer with the ice of the Greenland and Barents Seas combined, than with the ice of the Greenland Sea alone. It is interesting to note that the association of the temperature with the ice generally diminishes after the December-February quarter following the ice season, the correlation coefficients between the ice and the following March-May quarter temperatures being smaller than those with the temperatures of the September-November and December-February seasons before. Thus, the persistence of the processes associated with different types of ice conditions appears to extend for a limited number of months following the ice season.

The above results of the association of the ice with the precipitation in Iceland are not very different from those previously obtained for northern Norway (Schell, 1947) which lies in more or less the same zone of interrelation with respect to the Arctic ice. Thus, the correlation of the ice in the Greenland Sea with the following October-December precipitation of northern Norway, on recomputation with five additional years of data recently made available (1939, 1946-49), becomes $r = -.50$ $(n = 61)$.

Thus, the pattern of correlations obtained between the precipitation and the Arctic ice conforms with that expected from theoretical considerations. At the same time, the size of the correlation coefficient tells us that the ice of the northern North Atlantic is but a partial index of the contemporary and following precipitation. To what extent more adequate observations of the Arctic ice that may some day be available might alter the indications obtained at present remains to be seen.

3. Relationship with the preceding, contemporary, and following sea surface temperatures in the northern North Atlantic.

In outlining the general relationship of the ice in the Arctic with the ocean circulation in that general area, it has been assumed that the fluctuations in the ice are associated also with changes in the temperature of the Arctic waters; a more southerly limit of the ice in the Greenland Sea is associated with a well-developed flow of cold water from the north and lower temperatures; and, on the other hand, a more northerly limit of the ice, etc., is associated with a stronger Irminger Current

sweeping round to the north coast of Iceland from the south and with higher temperatures. It was further assumed that because of persistence of the circulation processes, the sea temperatures following the ice season would show the same trend as the temperatures contemporary with the ice season.

As the severity of the Arctic ice season off Iceland probably reflects the intensity of the East Icelandic Polar Current, we may expect a greater southeastward penetration of this Current in severe than in light ice years. Thus, Knudsen (1906) found that the 10° isotherm and 35.00 ‰ isohaline, which he took as an index of the southeastward extension of the East Icelandic Polar Current, lay between the Faroes and the Shetlands in 1902, a severe ice year, but well to the northwest of this position in 1903, a normal ice year off Iceland. More recently Hermann (1948) showed that the eastern boundary of the East Icelandic Polar Current in August, 1948 (35.00 ‰ isohaline at 100 m.), a very light ice year, intersected latitude 65°N at longitude 7°W, while in July-September, 1900, a less light ice year, this isohaline intersected the same latitude at longitude 2°30'W; and in August-September, 1903, a normal ice year, the point of intersection was at longitude 1°W.

In an attempt to define the Arctic ice as an index of the circulation in the Arctic and adjacent waters, it becomes necessary for lack of sufficient data on currents in these waters to examine this question indirectly by studying the longer series of sea surface temperatures now available. Accordingly, correlations were carried out between the ice of the Greenland Sea and the contemporary, following, and the preceding annual sea surface temperatures of a number of areas in the northern North Atlantic north of 50°N (Fig. 1) that have recently been tabulated by Smed (1947-1953) and also with the temperatures from a number of stations along Iceland's coasts as well as Thorshavn, etc. An attempt at differentiation of the water characteristics of the individual areas within this large area (Fig. 1) suggests that the waters in areas F, G, H, K, L, M, N, and Marsden Squares 252A,B and 251C,D (Fig. 1) are of warm Atlantic origin; the waters in areas A, B, C, and I, mainly of polar origin; and the waters in areas D, E, and J, in greater or lesser proportions of both origins.

Similarly, the waters at Papey off the east coast of Iceland are mainly of polar origin, those at Vestmanno on the south coast and Stykkisholm on the west coast are warm Atlantic in origin, while those at Grimso off the north coast show an intermingling of both polar and relatively warm Atlantic waters, all four stations reflecting to some extent the influence of the land mass on whose rim they lie. Equally, the waters at Thorshavn-Myggenaes, Port Erin, and along the coast of Norway are warm Atlantic in origin, and, except for Thornshavn, are to a greater or lesser degree influenced by the adjacent land masses.

The data for the areas A-N, except for area C which begins with the year 1905, generally cover the years 1876 to 1949, minus the six-year period 1940-45 and a portion of World War I period;

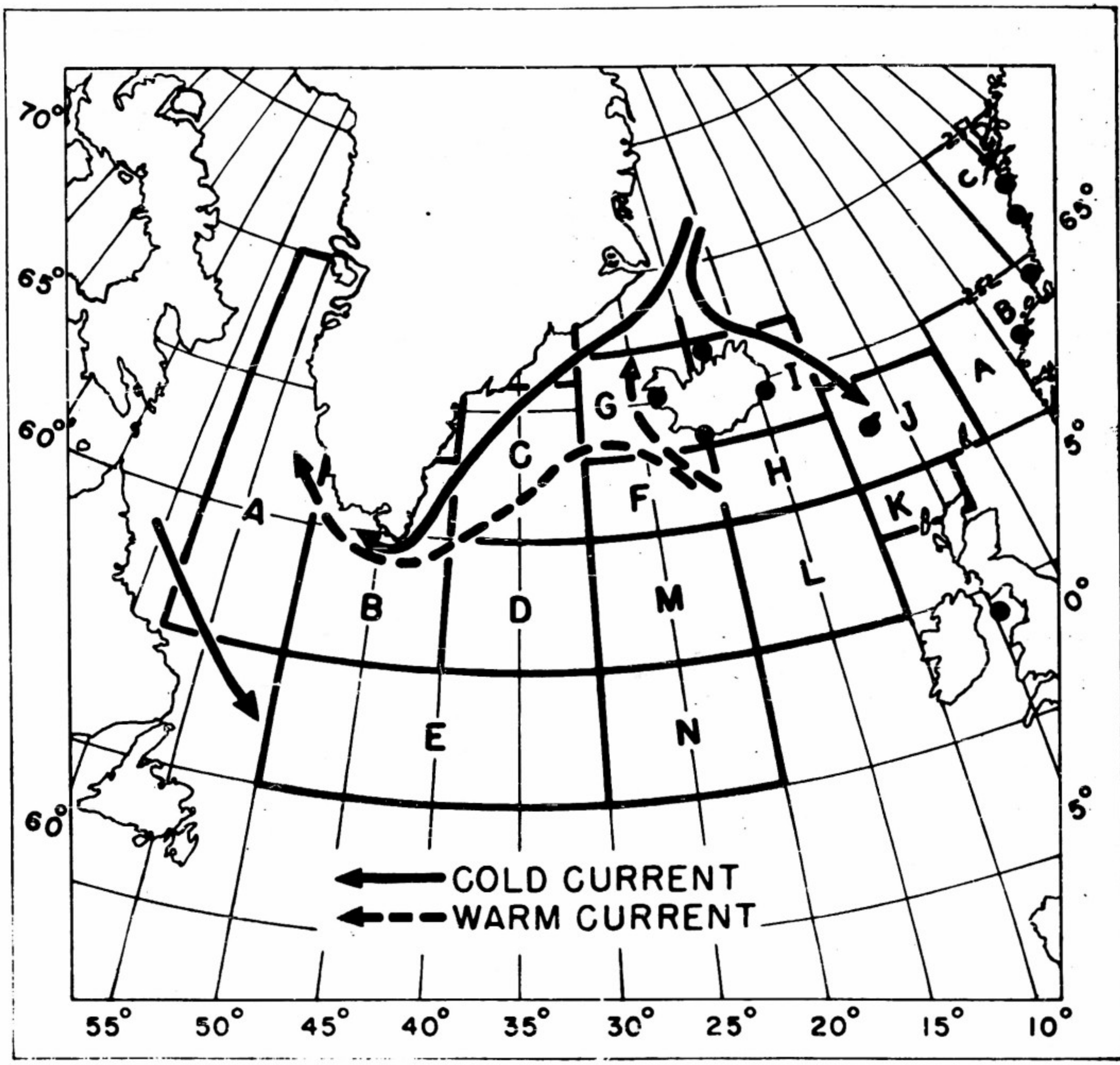

Fig. 1 Location of sea areas A to N (after Smed) and Marsden Squares 252A, 252B, 251C, 251D and of coastal and island stations (dots).

and thus provide approximately six decades of record in most cases for examination. However, the material, as might be expected, is sparse and quite uneven in that much fewer observations were made for most areas in the earlier than in later years, and practically no observations were available for the winter months until fairly recently from the more northerly areas. This shortcoming of the data is to a considerable extent offset by the conservativeness of the ocean processes. A more serious drawback to the material, as seen from Figure 1, is the mainly geographical delimitation of these areas, many of them representing water masses of mixed origin--warm Atlantic and Arctic.

Coefficients of correlation of the Greenland Sea ice with the ocean surface temperatures of the various areas were computed for a time lag of 0, 1, 2, and in some instances 3, 4, 5, and 6 years as well as -1, -2, -3 years, and are shown in Table 2 together with the separate set of coefficients based on the data from the four stations along the northern (Grimso), southern (Vestmanno), western (Stykkisholm), and eastern (Papey) coasts of Iceland, Thorshavn-Myggenaes in the Faroes, and others.

Because of the limiting nature of the manner in which the large area was divided, no large association of the sea temperature series with the Arctic ice could be expected; and it is perhaps no surprise that with a few exceptions the correlation coefficients obtained were quite small (Table 2). It is significant, however, that the sign of the coefficients is negative throughout, showing a tendency for below normal temperatures with severe ice conditions, etc., as was to be expected. To a certain extent, the negative sign of the correlation coefficients obtained is probably due to the recent climatic trend, since the negative correlation of the Greenland Sea ice with the sea surface temperatures here examined is not limited to the more northerly areas but includes the warm water areas.

The fact that in several instances the coefficients of correlation obtained increase following the year of the ice season and that with one or two exceptions they are smallest for the year before the ice would lead us to conclude that the Arctic ice is more a precursor of the future sea surface temperature than an index of the temperature contemporary with the ice season and that the preceding sea surface temperature bears very little relation to the Arctic ice. This is perhaps as it should be, since it can be assumed that it would take the Arctic water longer to travel to the south and to assert its influence there than it would take the ice to cover the same distance.

In addition to the correlations of the Greenland Sea ice with the annual temperatures of the 14 areas, the four coastal stations of Iceland, etc., a separate set of correlation coefficients was obtained of the Greenland Sea ice as well as the Greenland Sea and Barents Sea ice combined with Papey and Thorshavn sea surface temperature for each season contemporary with (March-May, etc.) and following the ice season (September-November, etc.)(Table 3). Papey was chosen because this station lies close to an area with

Table 2. Correlation of Greenland Sea ice with the annual (-2, -1, 0, 1, 2, 3, 4, 5) sea surface temperature of the North Atlantic (north of 50°N) by areas (after Smed) and of coastal stations of Iceland, northern Norway, Thorshavn-Myggenaes, and Port Erin.

		Years							
Areas:		-2	-1	0	1	2	3	4	5
		r	r	r	r	r	r	r	r
A			-.13	-.33	-.35	-.40	-.40	-.26	
B			-.07	-.26	-.25	-.30	-.46	-.28	
C		-.35	-.37	-.56	-.33	-.37	-.58	-.54	-.38
D			-.04	-.22	-.19	-.29	-.38	-.18	
E			-.06	-.01	-.14	-.05			
F			.03	-.27	-.20	-.29	-.43	-.26	
G			.08	-.23	-.21	-.21	-.33	-.34	-.16
H			-.15	-.27	-.33	-.34	-.44	-.45	-.36
I			-.20	-.42	-.42	-.25	-.27		
J		-.14	-.30	-.27	-.30	-.15			
K			-.23	-.32	-.35	-.33	-.24		
L			-.19	-.38	-.33	-.27	-.39	-.29	
M			-.09	-.20	-.25	-.25	-.30	-.16	
N			.09	.01	-.03	-.02			
Stations:									
Grimsey	Iceland		-.16	-.37	-.45	-.09			
Papey	"		-.25	-.47	-.49	-.20			
Vestmanno	"		-.24	-.43	-.34	-.27			
Stykkisholm	"		.03	-.07	-.09				
Thorsh./Myg.	Faroes		-.24	-.35	-.22	-.11			
Ona	Norway		-.16	-.20	-.07				
Nordoyen	"		-.29	-.25	-.20				
Port Erin,	Irish Sea	-.09	-.39	-.29	-.29				

a single well-defined Arctic flow (East Icelandic Polar Current), while the choice of Thorshavn in the Faroes was determined by the consideration that the East Icelandic Current approaches these islands. The results obtained indeed show a close correlation of the ice with the Papey sea surface temperature and also indicate, as before, that the association of the ice with the polar water temperatures is closer, not with the season contemporary with the ice (March-August), but with the season following it (September-February). Similarly, the correlations obtained with the Thorshavn sea surface temperature, which are only a little less than those with Papey (Table 3), additionally indicate that the ice of the Greenland and Barents Seas probably reflects in a marked measure the intensity of the East Icelandic Polar Current as it approaches the Faroes. Thus, the ice during April-August is a significant index of the following fall-winter sea surface temperature along the course of the East Icelandic Polar Current.

4. Relationship with the longer period variations in the ocean temperature, precipitation, and cyclonic distribution in the northern North Atlantic and adjacent areas.

a. Decadal sea surface temperatures

1) Introductory

The longer series of ocean surface temperatures from the 14 areas in the open northern North Atlantic and from the four stations in Iceland, etc. (Fig. 1), considered previously in relation to the annual values of the ice in the Greenland and Barents Seas, were here examined in relation to the ice variations over longer periods. Before proceeding it is desirable to examine the general trend in the sea surface temperature in recent decades.

Considerable evidence exists by now that the water temperatures in many areas have undergone a marked rise much the same as the air temperature has in recent decades over a wide portion of the globe, though, as one might have expected, one smaller in magnitude. Evidence of this temperature rise over the northern North Atlantic (north of 50°N) has been most fully given by Smed (1947, 1949). The upward temperature trend is also evident along the east coast of the United States where at Boston, for example, the average annual sea surface temperature rose from 49.0°F. for the first half (1922-37) of the period examined (1922-53) to 50.9°F. the second half (1938-53) of the same period. Similarly, at Cristobal (Panama Canal Zone), where regular water surface temperature observations have been made since 1908, the annual temperature at that station rose from an average of 82.0°F. for the period 1908-30 to a value of 82.9°F. for the more recent period 1931-52. As the standard deviation (σ) of this temperature series is only 0.76°F., the rise experienced fully attests to the significance of the change.

Treating the question of the changes in the sea surface temperature during recent years in more detail, it would appear from

Table 3. Correlation of Greenland Sea and Greenland and Barents Seas ice combined with the contemporary (March-May, June-August) and following the ice, seasons (September-November, December-February, March-May) sea surface temperature at Papey (Iceland) and Thorshavn-Myggenaes (Faroes).

A. Greenland and Barents Seas Ice combined

	Contemporary			Following			
	Mar-May	Jun-Aug	Mar-Aug	Sep-Nov	Dec-Feb	Sep-Feb	Mar-May
	r	r	r	r	r	r	r
Papey (1895-1949)*	-.35	-.39	-.45	-.49	-.50	-.64	-.37
Thors.-Myg. (1895-1949)**	-.19	-.38	-.32	-.50	-.46	-.57	-.26

B. Greenland Sea Ice

	r	r	r	r	r	r	r
Papey (1877-1949)*	-.36	-.45	-.45	-.42	-.31	-.46	-.36
Thors.-Myg.(1877-1949)**	-.21	-.32	-.32	-.32	-.26	-.35	-.22

* 1940-45 are missing
** 1893-94, 1940-45 are missing

a study by Sandstrom (1942) of the interdecadal changes in the mean January sea surface temperatures in the northern North Atlantic that for the area as a whole the net change from the ten-year period 1900-09 to the period following it, 1910-19, was approximately nil; that from 1910-19 to 1920-29, markedly positive; and that from 1920-29 to 1930-39, also positive though not as marked. Similarly, from a more recent study by Brown (ibid.) giving the mean decadal anomalies of the sea surface temperature in four 5° squares in the area 60°-70°N, 20°-0°E, it appears (Table 4) that the average change in the sea surface temperature was 0.1°C. from the period 1900-09 to 1910-19; 0.3°C. from the period 1910-19 to 1920-29; 1.2°C. from the period 1920-29 to 1930-39; and -0.2°C. from the latter ten-year period to the 1940-49 period, the last finding suggesting a reversal of the upward trend of the sea surface temperature in that area in the late 1940's*.

An examination of the interdecadal variations in the ocean surface temperatures in the northern North Atlantic based on all the data from the various areas, etc., discussed above, shows the temperatures for the broad area as a whole to have risen from the preceding decade in each of the decades 1891-00, 1921-30, 1931-40 (Table 4); to have fallen from the preceding decade in the decade 1901-10, and partially in the decades 1911-20 and 1941-50.

Examining the results in more detail, the rise in temperature in the decade 1891-1900 from the decade preceding it held for all but two of the areas (Table 4) and for four of the six stations existing at the time, while the rise in the decades 1921-30 and 1931-40 held for all areas and stations but three and was also considerably greater (Table 4) than for the earlier decades.

Similarly, the fall in ocean temperatures in the decade 1901-10 from the preceding decade (Table 4) was almost as widespread but not as large as the temperature rises in the 1921-40 period, while for the decade 1911-20 and the recently ended decade 1941-50 there were areas in almost equal numbers, both with a rise and a fall in the temperature from the preceding decade. Thus, while the same temperature trend appears to have generally prevailed almost throughout the entire area irrespective of origin of the water masses in most of the earlier decades, the decade 1941-50 and to a certain extent the decade 1911-20 represent periods with conflicting tendencies in the temperature trend and therefore a steeper temperature gradient as between some of the areas. Much the same results were obtained on the basis of the more numerous observations provided by the coastal or island stations (Table 4).

To what extent the temperature rise in recent decades in the northern North Atlantic has been due to a greater inflow of warmer water from the south, the very marked increase in the temperature of the air above, or a possible increase in local insolation is

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* Both decades 1910-19, 1940-49 were deficient in observations due to military operations.

Table 4. Interdecadal variations in the sea surface temperature in the northern North Atlantic (north of 50°N) in (1) areas A to N (after Smed); (2) Marsden Squares 251C,D; 252A,B (after Brown); and (3) 10 coastal stations and interdecadal variations in the character of the ice off Iceland and in the southerly limit of the ice in the Greenland and Barents Seas combined (1881-90/1891-00 - 1931-40/1941-50).

	Period					
Area	1881-90/ 1891-00	1891-00/ 1901-10	1901-10/ 1911-20	1911-20/ 1921-30	1921-30/ 1931-40	1931-40/ 1941-50
	°C	°C	°C	°C	°C	°C
A	-0.1	-0.1	-0.1	0.9	-0.1	-0.1
B	0.1	-0.3	-0.1	0.7	0.0	-0.4
C	--	--	--	0.4	0.5	-0.3
D	0.3	-0.6	0.1	0.2	0.4	-0.1
E	0.2	-0.7	-0.1	0.2	0.6	-0.8
F	0.2	-0.3	-0.2	0.2	0.5	0.1
G	0.3	-0.3	0.0	0.0	0.7	0.1
H	0.1	-0.1	-0.2	0.2	0.4	0.4
I	0.4	-0.1	0.1	0.1	0.7	0.2
J	-0.1	0.0	-0.1	0.1	0.5	0.4
K	0.1	-0.3	0.0	0.2	0.3	0.4
L	0.2	-0.4	0.0	0.1	0.5	0.2
M	0.4	-0.6	-0.1	0.1	0.6	-0.2
N	0.5	-0.6	-0.1	-0.1	--	--
Average:	0.2	-0.3	-0.1	0.2	0.4	0.0
Marsden Square						
252A	--	--	0.1	0.4	0.9	-0.2
252B	--	--	0.1	-0.1	1.6	-0.4
251C	--	--	0.2	0.5	1.1	-0.3
251D	--	--	0.0	0.4	1.3	0.1
Average:	--	--	0.1	0.3	1.2	-0.2
Vestmanno	0.4	0.1	0.1	0.6	0.4	0.1
Stykkisholm	-0.4	0.1	0.3	0.2	0.1	-0.3
Grimsey	0.3	-0.4	0.5	0.9	0.6	-0.6
Papey	0.4	0.1	0.0	1.0	0.5	-0.3
Port Erin	--	--	-0.2	0.4	0.1	-0.1
Myken	--	--	--	--	0.4	-0.3
Nordoyan	--	-0.1	0.4	0.1	0.4	-0.3
Skomvaer	--	--	--	--	0.7	-0.3
Ona	-0.1	0.1	0.0	0.1	0.5	-0.2
Thorsh./Myg.	0.2	-0.3	0.1	0.3	0.2	0.2
Average:	0.1	-0.1	0.2	0.4	0.4	-0.2
Ice Limit (°Lat.)*	--	--	0.6°	-1.1°	-0.2°	0.7°**
Ice off Iceland	Sv./Md.	Md./Md.	Md./Md.	Md./Lt.	Lt./Lt.	Lt./Md.**

* Minus sign signifies a northward displacement.
** Provisional.

impossible to say. Some evidence that the warming of the waters in the high latitudes was in fact due to a greater inflow of warmer water appears from a consideration of the warming pattern in recent years. Assuming that in the areas where the inflow of warmer water occurs earlier, the temperature rise would be greater than the simultaneous rise in the areas where the warmer water reaches in full strength later, than the rise in the sea surface temperatures off northern Norway would be expected to be greater than in the same period off southern Norway, where the warmer Atlantic water would be expected to reach later. Thus, Hesselberg found (1940) that the recent rise in the sea surface temperature off northern Norway ranged from 1.8° to 1.0°C., as compared with only 1.2°C. to 0.4°C. in the same period off southern Norway. Similarly, Smed (1947) found that the maximum rise in the surface temperatures occurred later in the North Sea than in the area farther to the north where the warm Atlantic water would be expected to arrive first (before sweeping down southward).

The probability that the rise in the ocean temperatures in the northern North Atlantic was largely due to a greater transport of warmer water from the south agrees with the fact that the atmospheric circulation pattern over the northern North Atlantic has altered markedly in recent decades and a marked increase of southerly winds has taken place (Eriksson, 1943). Additional evidence is provided by the increase in the salinities of these waters for the same period, as reported by Smed (1943) and Helland-Hansen (1949).

ii) Comparison with Arctic Ice

It has been variously shown that during the period under consideration, as well as previous to it, the character of the ice off Iceland has similarly undergone considerable changes from decade to decade as has the southerly limit of the ice in the Greenland and Barents Seas during the shorter period beginning with the 1901-10 decade, the first full decade for which information for this larger area is available. Table 4, giving the interdecadal variations in the character of the ice off Iceland earlier determined by the author (1952), and in the mean position of the decadal ice limit drawn from the individual ice limits given by the Danish Meteorological Institute, shows that the severity of the ice off Iceland has decreased from the preceding decade (or was so much below the normal that no further substantial decrease could occur) in the decades 1891-1900 (from severe to moderate); 1921-30 (moderate to light); 1931-40 (light to light); and has probably increased in the decade 1941-50* (light to moderate), though not in the decades 1901-10 and 1911-20. Similarly, the average southerly ice limit in the Greenland and Barents Seas lay farther north in the decades 1921-30 (-1.1° Lat.) and 1931-40

* No figures comparable to those obtained for the previous decades have yet been published but it is known that the ice character of this decade was not as light as that of the decade before and probably was moderate.

(-0.2° Lat.) than in each of the preceding decades, respectively, and correspondingly lay farther south in the decade 1911-20 (0.6° Lat.) and during the 1946-50 period (0.7° Lat.), the portion of the 1941-50 decade for which information on the ice limit is at present available.

Comparing the above pattern of changes in the ice with the changes in the sea surface temperatures given in Table 4, it is apparent that an increase in the decadal ocean temperature for the area as a whole generally coincided with the particular character of the ice off Iceland and the ice limit of the Greenland and Barents Seas, the increases in the ocean surface temperature in the northern North Atlantic during the decades 1891-1900, 1921-30, 1931-40 from the preceding decade corresponding to ice decreases. No such clear-cut relationship is evident, however, for the two decades 1901-10 and 1911-20.

In attempting to outline the possible relations of the ocean surface temperatures of the individual areas and stations with the Arctic ice, we are confronted as before with the question of the origin of the water masses of the different areas, etc. We might reasonably expect that the colder waters of this large area would show closer correlation with the ice than the warmer waters.

An examination of Table 4 shows that except for the recent decade 1941-50 and to a certain extent the decade 1911-20 this is not the case and that virtually all areas, irrespective of the type of water masses, showed either a simultaneous increase or decrease in the temperature for the same period. This would suggest that by and large the longer period variations in the Arctic ice and in the ocean surface temperatures in the northern North Atlantic are part of the same general longer period changes in the circulation in that large area, the Arctic ice and the sea surface temperature reflecting these deep-seated changes together.

b. Decadal precipitation

i) Introductory

The trends in the decadal sea temperatures discussed above and in the air temperature earlier (Schell, 1952) might be expected to be associated with corresponding trends in the decadal precipitation. As a result of the fall in pressure (Petterssen, 1949) and increase in southerly winds (Eriksson, ibid.) over the northern North Atlantic and adjacent areas in recent decades, higher precipitation would be expected during the same period in that general area, inasmuch as wetness and warmth over longer periods tend to coincide north of 55°N (Willett, 1952). Table 5 shows that in the region embracing Iceland, southernmost Greenland, Spitsbergen, and northernmost Europe variously represented by 10 to 14 stations (except by only two during the period 1861-1880), the precipitation was, in fact, above normal in the last three decades (1921-50) and close to normal or below in the decades before.

Table 5. Character of the ice off Iceland and the average latitude of the ice limit in the Greenland and Barents Seas combined and the annual precipitation by decade (1861-1950) in Iceland, southern Greenland, Spitsbergen, northernmost Europe, and region as a whole (n = number of stations).

	Ice		Precipitation					
Decade	off Iceland	Greenland and Barents Seas	Iceland	Southern Greenland	Spits-bergen	Northernmost Europe	Region	
		°N	%	%	%	%	%	n
1861-70	Severe	--	92	--	--	75	84	2
-80	Moderate	--	93	--	--	79	86	2
-90	Severe	--	94	104**	--	92	94	10
-00	Moderate	--	95	102**	--	98	98	11
1900-10	Moderate	71.8	100*	102	--	100	100	13
-20	Moderate	71.2	91*	99**	89**	96	95	13
-30	Light	72.3	109	89**	113**	103	104	14
-40	Light	72.5	110	128**	98**	108	109	14
-50	Moderate°	71.8°	100	98	--	104	102	11
Average (1881-1940)			1107 mm	1008 mm	322 mm	678 mm	960 mm	

o Provisional

* The values of Iceland's precipitation for the decade 1911-20 and to a lesser extent for the decade 1901-10 are too low due to the poor exposure to the rain-gauge at Stykkisholm, one of the stations employed, during much of this period. ("A considerable amount of precipitation occurring during periods of east and south winds got lost". Personal communication from Mr. H. Sigtryggsson, Icelandic Weather Service).

** All the Spitsbergen values and the Greenland values for 1881-1900, 1911-40, are single station values.

ii) Comparison with Arctic ice

1) Contemporary conditions

In an attempt to show the existence of a general relationship between the ice in the Arctic and the precipitation, a comparison of the available precipitation data from Iceland (1), southernmost Greenland (2), Spitsbergen (3), and northernmost Europe (4) was made with the ice off Iceland, as was done earlier with the temperature and then with the average latitude of the ice limit in the Greenland and Barents Seas combined. Although the general character of the ice in the Greenland and Barents Seas when considered by decade is very similar to the character of the ice off Iceland, it was thought desirable to take advantage of the areally more extensive though shorter ice series since become available, to study the relation of the precipitation with the ice in the Arctic on a broader basis. Accordingly, our comparison of the precipitation with the severity of the ice off Iceland begins with the decade 1861-70, the first such full decade with corresponding precipitation observations, and that with the average latitude of the ice limit in the Greenland and Barents Seas combined starts with the 1901-10 decade, the first full decade when ice values for this larger area are available.

Table 5 shows that the precipitation in the two decades with light ice conditions off Iceland occurring together (1921-40) and coinciding also with a less southerly extension of the ice in the Greenland and Barents Seas was above the long-term average, as follows (average of both decades): Iceland, 109.5%; southernmost Greenland, 108.5%; Spitsbergen, 105.5%; northernmost Europe, 105.5%; region as a whole, 106.5%. On the contrary, the precipitation in the severe ice decade 1881-90 was, except for Greenland, below the average as follows: Iceland, 94%; southernmost Greenland, 104%; northernmost Europe, 92%; region as a whole, 94%. Similarly, in the other severe ice decade 1861-70 the precipitation was also below the average: Stykkisholm 92%; Haparanda, 75%.

Although none of the decades after 1881-90 can be considered as having had severe ice conditions in the sense used for Iceland, the average limit of the ice in the combined Greenland and Barents Seas in the decade 1911-20 extended farther south than in any of the other four decades for which similar measurements are available. Table 5 shows that the precipitation of this decade was indeed below the average (95% for the region as a whole).

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(1) Stykkisholm, Berufjord, and Vestmanno.
(2) Ivigtut, whose record for the decade 1921-30 was too incomplete to be included; and Angmagsalik, whose record begins with 1898.
(3) Record begins with 1912 and values are missing for a number of years including the World War II period.
(4) Bodo, Tromso, Bronnoysund, and Vardo in northern Norway; Karesuando and Haparanda in northern Sweden; Kaajani and Sodankyla in northern Finland; and Archangel in northern Russia.

From the foregoing it is evident that the decadal precipitation in the Icelandic, etc., areas varies with the southerly extent of the ice in the sector of the Arctic examined. A more southerly position of the ice limit, etc., is accompanied by lighter precipitation over thatarea and, conversely, a more northerly position of the ice limit, etc., by heavier precipitation.

2) Preceding conditions

In the treatment of the relation of the decadal air temperature of Iceland, etc., with the ice off Iceland (Schell, 1952) it was shown that following a decade with extreme ice conditions the temperature departure of Iceland and northernmost Europe tends to retain the sign of the departure of the previous decade, below normal temperatures being maintained following severe ice conditions and above normal temperatures following light ice conditions. It was suggested at the time that this carry-over relationship is due to the persistence of the circulation associated with one or another type of extreme ice conditions and presumably with a greater or lesser outpouring of Arctic water, the water, and to a lesser extent, the ice, contributing to the maintenance of the time-lag relationship.

From this we may infer that the precipitation pattern will also show a similar relation with the Arctic ice and, hence, following severe ice conditions; for example, the below normal precipitation trend in the northern North Atlantic and adjacent areas that is associated with severe ice would be maintained for some time afterwards, provided no radical change in the circulation and in the corresponding ice character from the previous decade has occurred.

Table 5 shows that the precipitation in the decades 1871-80 and 1891-1900, both following the severe ice decades 1861-70 and 1881-90, respectively, was below the average, as follows: Iceland (Stykkisholm only), 93%; northernmost Europe (Haparanda only), 79%, for the decade 1871-80; and Iceland, southernmost Greenland, and northernmost Europe combined (11 stations), 98% for the decade 1891-1900.

Similarly, the precipitation in the decades 1931-40 and 1941-50 following the light ice decades 1921-30 and 1931-40, respectively, was above the average, as follows: Iceland, 110%; southermost Greenland, 108%; Spitsbergen, 98%; northernmost Europe, 108%; region as a whole, 109% for the decade 1931-40 and, again, region as a whole, 102% for the decade 1941-50.

The higher value of the precipitation for the decade 1931-40 than for the decade 1941-50 is probably due to the decade 1931-40 being both a decade with light ice and one following a decade with light ice. (The decade 1941-50 followed but probably was, it appears, a decade with moderate ice.) We may, therefore, conclude that the precipitation trend in the northern North Atlantic and adjacent areas follows a pattern similar to that followed by the temperature, etc., namely, the pattern associated with extreme ice conditions tending to persist for some time afterwards.

c. Decadal storminess and comparison with Arctic ice

The relation of the ice in the Greenland and Barents Seas with the air and sea temperatures and precipitation noted above would be expected to involve also a relation with the storminess. In accordance with the pattern of interrelations drawn above we may expect a more southerly extension of the ice boundary, for example, to be associated with a less northerly position of the mean northern North Atlantic storm track and, on the assumption that a more polar development in the North Atlantic-Arctic and a shallower North Atlantic low would lead to less steep S to N pressure gradients, also expect fewer storms. Additionally, with a tendency towards persistence in the circulation associated with different ice extremes, we may expect the storminess pattern corresponding to severe and light ice conditions, respectively, to similarly persist.

Evidence of a relation between the latitude of the mean storm track in the northern North Atlantic during the ice season and the season following it was previously given by Wiese (ibid.) on the basis of the variations in the ice of the Greenland Sea, the average latitude of the storm track in the summer contemporary with a heavy ice season, and in the fall following it, being several degrees farther south than in the summer and fall contemporary with and following a light ice season, and similarly, the frequency of storms, being smaller with a severe than with a light ice season.

We might therefore expect the relation of the storminess with the Arctic ice noted above to hold for ice variations over longer time intervals as well, and hence, during and following a decade with severe ice conditions, for example, for the mean storm track to lie farther south and for the storminess to be less frequent than during, etc., a decade with light ice conditions.

As a test of the above, decadal values of the annual storm frequency and mean altitude of the storm track based on a compilation of annual frequencies of closed low pressure systems recently obtained by Pollak and O'Brien (1951) for the period 1901-38 were first prepared for the area 45°-70°N, 0°-70°W. Table 6 shows, however, a marked decrease in the annual frequency of the storms in this particular area from the first part (1901-20) to the second part (1921-38) of this period, with the lowest annual frequency being registered for the years 1931-38. Thus, for this area as a whole the annual frequency has decreased from a high of 626.8 per annum for the decade 1911-20 to a value of 541.3 for the period 1931-38 and from an annual value of 619.4 for the first two decades 1901-20 to a value of 567.4 as the average of the period 1921-38.

As against the marked change in the annual frequency of storms for the different periods examined that was noted above, no perceptible variation from one decade to another, etc., is shown in the mean latitude of the storm track, however (Table 6, last column) and neither result which is based on the values of

Table 6. Annual frequency (f)* of storms (closed low pressure systems) for each 5° zone of latitude and mean latitude (L) of storm track in the area: 0°-70°W, 45°-70°N by decade, etc., during 1901-38.

Zone (°N):	70°-65°	65°-60°	60°-55°	55°-50°	50°-45°	70°-45°N	
	f	f	f	f	f	f	L°N
1901-10	105.6	131.0	122.6	135.9	116.8	611.9	57.3
11-20	100.4	153.1	115.3	140.9	117.1	626.8	57.3
21-30	103.3	127.0	115.6	133.6	114.1	593.6	57.3
31-38	95.7	125.4	103.2	112.3	104.7	541.3	57.5
1901-20	103.0	142.0	119.0	138.4	117.0	619.4	57.3
21-38	99.5	126.2	109.4	123.0	109.4	567.4	57.4
Difference:	3.5	15.8	9.6	15.4	7.6	52.0	-0.1

* Because a low appearing in one section of this zone may appear later in another section of the same zone, the figures shown naturally often represent repetitions.

storminess in the area (45°-70°N, 0°-70°W) is consistent with the premises and earlier findings referred to above which call for a greater frequency of storms and for a more northerly position of the mean latitude of the storm track during the period 1921-38 (light ice conditions) than during the preceding two decades 1901-20 (relatively heavy ice conditions).

A feature of Table 6 that draws special attention is the much smaller decrease from the first part to the second part of the period examined in the annual frequency of storms in the zone 65°-70°N, especially as compared with the neighboring zone (3.5 units for the zone 65°-70°N as compared with 15.8 in the zone 60°-65°N). This sharp S to N tapering off in the storm frequency difference from the first part to the second part of the period examined, in the zone 60°-70°N, permits us to suppose that if this trend were to continue north of latitude 70°N, an increase rather than a decrease in the annual frequency would be the result, and hence that the mean path of the storm track would lie farther north in the more recent period with light ice conditions (1921-38) than in the preceding period with heavier ice conditions (1901-20) as was to be expected originally.

As the values made available from the tabulations by Pollak and O'Brien (ibid.) do not go beyond 70°N, we cannot test this point in the manner employed above. We can, however, make a partial test by examining the differences in the winter cyclonic frequencies between the 1900-19 and 1920-39 periods recently given by Petterssen (ibid.) for substantially the same area as used here but which fortunately include the zone 70°-75°N as well. The presentation of the results by Petterssen is somewhat different than employed here. Nonetheless, we find for the quadrilateral 70°-75°N, 10°E to 30°W a very substantial increase in the cyclonic frequency in the 1920-39 period over the 1900-19 period, all the other areas south of this zone showing a decrease in the cyclonic frequency as was the case with our own findings. This would suggest that if the results for the remaining three seasons (March-May, etc.) similarly show an increase in the cyclonic frequency, then the frequency of storms in the northern North Atlantic north of latitude 70°N would indeed have been greater with light than with heavy ice conditions and that the mean latitude of the storm track in the same area would have followed the northward retreat of the southerly limit of the ice in recent years, as was to be expected. (As the increase for the quadrilateral 10°E-30°W, 70°-75°N outweighs the decrease for the much larger area 50°-70°N between the same longitudes, the above can be said for this larger area as a whole.)

The above result is to a certain extent corroborated also by the experience of the more recent expeditions in the Arctic (North Pole station, Sedov) which have recorded storms with a frequency far greater than that observed by members of the FRAM and other expeditions of an earlier period.

5. Relationship with the mean monthly net air transfer in the Arctic

Because of the apparent relation of the pressure in the North Atlantic-Arctic and adjacent areas to the ice in the Greenland and Barents Seas, we might expect that the mean monthly net air transfer, or inflow and outflow of air, respectively, from the Arctic would be related to the variations in the ice.

To probe this, values of the net change in the mean monthly pressure from each month to the month following it (i.e., January to February) based on northern hemisphere pressure profile data, 1899-1939 inclusive, were computed for the Arctic sector (60°N-90°N) and for the northern hemisphere as a whole (north of 20°N), due allowance being made for the decrease in total mass of air with increase in latitude. The respective values of the monthly net air transfer (average pressure change), derived as running means of the three consecutive months, are shown in Table 7.

It appears that the net inflow of air into the Arctic sector begins approximately in October and continues through March, which are the times of the year with the least and the greatest ice cover in the Arctic, respectively. On the other hand, for the northern hemisphere as a whole (20°N-90°N) the inflow begins in August and the outflow in February.

Table 7. Mean monthly average pressure change (running means of three months) from one month to the next in the Arctic sector and in the northern hemisphere (20°N-90°N) as a whole in mb.

Sector	Jan*	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60°-90°N:	0.6	0.6	0.6	0.0	-1.0	-1.2	-1.0	-0.3	0.0	0.5	0.8	0.8
20°-90°N:	0.0	-0.2	-0.6	-0.6	-1.1	-0.9	-0.5	0.4	0.8	1.0	0.8	0.6

* The month to which the change is reckoned, thus, the change from December to January.

The apparent over-all relation between the development of the ice cover in the Arctic and monthly transfer of air to and from the Arctic sector (60°N-90°N) suggests that there may also be a relation between the changes in the yearly and longer period variations in the ice cover and the corresponding air transfer. Lacking yearly values of air transfer for the Arctic sector, we may examine the possibility of such a relation for the northern hemisphere as a whole, fully expecting the relation with the hemisphere as a whole to be far less close than with the Arctic sector alone.

On correlating the yearly values of the ice in the Barents and Greenland Seas with the corresponding northern hemisphere

pressures (north of 20°N) based on the 41-year period 1899-1939, we obtain the coefficient of correlation: $r = 0.38$, indicating some tendency for more ice in the North Atlantic-Arctic to be associated with higher pressures, etc., in the northern hemisphere (north of 20°N), etc. Again, the average pressure or total mass of air over the northern hemisphere (north of 20°N) for the 20-year period 1901-20, with relatively severe ice conditions (average latitude of ice limit: 71.6°N) was 0.28 mb above the 39-year average 1015.20 mb (1901-39) as against 0.29 mb below the average for the 19-year period 1921-39* with light ice conditions (ice limit: 72.5°) (Table 8).

Table 8. Departure from average pressure in the northern hemisphere (north of 20°N) and mean latitude of ice limit in the Barents and Greenland Seas.

Period	Pressure mb	Ice Limit °N
1901-20	0.28	71.6
1921-39	-0.29	72.5**

** The difference of only 0.9 degrees of latitude between the two periods is in part due to the very small fluctuations in the ice limit between Cape Farewell and west of Iceland. For the area, from west of Iceland to Novaya Zemlya, the average difference is nearly two degrees.

F. Discussion

In considering the Arctic ice as an index of the contemporary and to a certain extent the following weather conditions in the Arctic and adjacent areas, it was assumed that the relationships of the Arctic ice with the weather owe their existence primarily to varying outflows of water from the Arctic and that the ice reflects the intensity of these outflows. An indirect attempt to corroborate these relationships was also made by correlating the Greenland Sea and Barents Sea ice with the sea surface temperature of the northern North Atlantic. It would be reasonable to assume, therefore, that by employing the ocean temperatures directly in the correlation with the precipitation of Iceland, for example, we should obtain at least as good a correlation as was obtained with the Arctic ice itself. As a test we have selected the mean March-August Papey sea surface temperatures which, owing to this station's location on an island 6 miles off the east coast of Iceland, may be assumed better to reflect the changes in the Arctic water outflow (East Icelandic Polar Current) than the temperatures of any of the other areas from which data are available; and later we correlated these temperatures with the following September-November and September-February precipitation of

* For the year 1939, only the first six months pressures were available.

Iceland. The coefficients obtained had a value, r, less than 0.2.

The reason for the lack of a relationship between the sea surface temperatures and the following precipitation of Iceland becomes clear, perhaps, if we remember that the coldness of the water off the east coast of Iceland is probably only partially a measure of the intensity of the East Icelandic Polar Current. What has been regarded as most significant in our scheme of things was, we may recall, the degree of penetration of Arctic water southward; and this we can assume is reflected better by the presence or absence of Arctic ice which is associated with a movement of the water and air rather than simply with the temperature of the water which, in addition to reflecting the intensity of the Arctic outflow, also reflects chilling from above, mixing with subsurface water, etc., all of which may be little related to the degree of penetration of the cold water to lower latitudes.

Strange as it may seem, no attention to date has been paid to the question of relationships of the weather, etc., with ice in North Pacific-Arctic (Bering Sea, Chuckchee Sea). The variations in the ice of the North Atlantic-Arctic (Greenland and Barents Seas combined) and in the ice of the North Pacific-Arctic (Bering and Chuckchee Seas combined) might be expected to be similar in character if it is assumed that the broad changes in the circulation which determine the changes in the ice are circumlatitudinal in character.

As a preliminary test of a possible relationship between the southerly extension of the ice of the two regions, the annual values of the North Pacific-Arctic ice for the 43-year period 1901-39, 1946-49 was correlated with the simultaneous variations in the ice of the North Atlantic-Arctic. The correlation coefficient obtained is r, -0.45, which suggests some tendency for the southern boundary of the ice in the North Atlantic-Arctic to retreat while its boundary in the North Pacific-Arctic extends southward, and vice versa*. This is unlikely to involve a shift in the pack itself, however, but probably reflects the tendency earlier indicated by Walker (1932) for the North Pacific and North Atlantic circulations not to act in unison with each other and thus for different type relationships with the ice cover in these two Arctic areas.

The results obtained here are on the whole favorable for the theory that the Arctic ice can, to a certain extent, serve as an index of the contemporary and also following ocean and air temperatures, precipitation, etc., in the Arctic and adjacent areas; and they also show that in some instances, as in the case of Papey and Thorshavn-Myggenaes, for example, the Arctic ice is a better

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* For longer-period ice variations, the tendency for the ice in the North Pacific-Arctic not to vary in the same sense as in the North Atlantic-Arctic appears more marked. Thus, while the average ice limit in the North Atlantic-Arctic appears to have decreased by 18% from the 1901-20 to the following 1921-39 period, it has apparently increased by 22% during the second period on the North Pacific side of the Arctic.

index of the following sea surface temperatures than of those contemporary with the ice. It is equally apparent from the results obtained to date that the ice is not a major index of the ocean and air circulation, although to what extent improved ice observations may alter this verdict remains to be seen. We may therefore feel that from a practical standpoint we need not occupy ourselves too much with the question of Arctic ice relationships. The bald fact, however, is that we have not as yet been able to seize upon any other criterion that could serve as good an index of the following weather in some of the areas here outlined, the one other coordinated attempt to determine possible relationships with the September-February temperature in the Arctic fringe areas from a correlation with the preceding North Atlantic Oscillation (Walker and Bliss, 1936) having yielded minimal results. As the Arctic ice emerges as the only criterion to date of the following September-February ocean and air temperatures, etc., and to a certain extent also of the following longer-period trends in the Arctic, etc., areas, we might, using the Arctic ice as a starting point, develop additional indices of the circulation to form together a basis for foreshadowing the weather in the Arctic and adjacent areas.

In assuming that with a more southerly extension of the Arctic ice, for example (associated with a more polar development in Arctic and adjacent areas and a tendency to a flattening of the North Atlantic low pressure field), we should expect a lesser exchange of air between the high and lower latitudes and, therefore, a decrease in storminess, we have omitted mentioning that with severe ice conditions a need also arises for a greater exchange of air between the same latitudes due to a steepening of the S to N temperature gradient. Thus two opposing tendencies eventually come into being, though not simultaneously, with the evidence submitted in this paper and in earlier papers pointing to the dominating role of the tendency for fewer storms with severe ice, etc. The effect of the opposing tendency for an increase in storminess, etc., with severe ice, however, prevents the Arctic ice from becoming a major index of the circulation and weather in the Arctic and adjacent areas.

It has been earlier suggested that the relation of the longer-period variations in the Arctic ice with the temperature, precipitation, etc., indicated here and elsewhere (Schell, 1952) on the basis of the ice, etc., data during the past 12 or fewer decades may serve as a guide to the conditions in earlier years when only ice observations were made. We find that a period as poor in ice off Iceland as that from 1919 to 1943 has not occurred since the middle of the 18th century and if we can trust the records prior to the 1750's as well, it would then be more accurate to say since the middle of the 17th century. This would suggest that the recent relatively warm and wet period in the North Atlantic-Arctic and adjacent areas may not have been earlier duplicated for 200 years or more.

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